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REGION OF THE ZT-40M EXPERIMENT

AUTHOR(S): H. Makowitz,\* Consultant to CTR-2

\* On leave of absence from B1 National Laboratory at  
the Institute for Fusion St astin, Texas

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**Los Alamos** Los Alamos National Laboratory  
Los Alamos, New Mexico 87545

## A STUDY OF LIMITER DAMAGE IN A MAGNETIC FIELD ERROR REGION OF THE ZT-40M EXPERIMENT

H. Makowitz\*, Consultant to CTR-2

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

A study has been initiated of material plasma interactions on the ZT-40M, Reversed Field Pinch (RFP) plasma physics confinement experiment at Los Alamos National Laboratory. Observations of the evaporation and cracking of TiC coatings, initially placed on an AXF-5Q Graphite mushroom limiter, installed in a high field error region (e.g. an experimental vacuum vessel/liner port) were investigated. A parametric study was performed of the thermal and stress behavior of the limiter and coating materials undergoing plasma material heat exchange processes, in order to infer the magnitude of heat flux necessary to explain the observed material damage. In addition the vacuum (liner) wall material behavior was studied parametrically using the same heat flux values as the limiter study. A one-dimensional conduction model was used with applied heat and radiation boundary conditions, for predicting temperature distributions in space and time, where the thermal stress was calculated using a restrained in bending only plate model. Wall loadings corresponding to first wall, limiter energy fluxes ranging between  $1 \times 10^2$  W/cm<sup>2</sup> and  $1 \times 10^5$  W/cm<sup>2</sup> were used as parameters with plasma material interaction times ( $\tau_{00}$ ) between 0.5 ms and 10 ms. Short plasma energy deposition time ( $\tau_{00} > 10$  ms) spacial and time histories of temperature and stress were calculated for SS-304, Inconel-625, TiC and AXF-5Q Graphite materials. The parametric study indicates that for  $\tau_{00} \sim 6$  ms a wall loading of  $\sim 1 \times 10^4$  W/cm<sup>2</sup> results in the melting of Inconel and SS-304 first wall material and a loading of  $< 5 \times 10^4$  W/cm<sup>2</sup> results in the melting of TiC and Graphite. For Inconel, stresses in excess of the tensile strength occur for  $Q_0$  greater  $1 \times 10^3$  W/cm<sup>2</sup>. The same is true for SS-304. For Graphite AXF-5Q the tensile strength is exceeded for  $Q_0 \geq 1 \times 10^4$  W/cm<sup>2</sup>. From the observations of damage and the parametric results calculated it can be inferred that an energy flux of  $1 \times 10^4$  W/cm<sup>2</sup>  $\leq Q_0 \leq 5 \times 10^4$  W/cm<sup>2</sup> was observed over a time scale of  $5$  ms  $\leq \tau_{00} \leq 10$  ms in the field error region, if the model considered is relevant to the phenomenon in question.

### 1. DISCUSSION

A parametric study was performed using the TASS<sup>1</sup> computer code. This code was developed for system study purposes, and hence due to its general nature was not optimized for the problem presently being analyzed. The physics model used consisted of a flat plate exposed to a heat flux  $Q_0$  for time  $t$ , with radiation boundary conditions for both surfaces, to  $T_{w1}$  and  $T_{w2}$  the surface temperatures of the inner and outer walls relative to the limiter/first wall surface. The basic equation, Eq. (1), is formulated in dimensionless form, Eq. (2), and subject to a stability and convergence criterion, Eq. (3). The boundary conditions,

Eqs. (4) and (5), are formulated in dimensionless form, Eq. (8) and Eq. (9). The thermal stress model used, Eq. (10), is solved using Simpson's rule, Eq. (11), for a given temperature distribution at time  $t$ .

Convergence and stability analysis, for low power cases, indicated that for long time ( $\sim 10$  s) cases a time step of 0.2 ms and a spacial mesh size of 15 nodes/linear cm were sufficient. Finer mesh and smaller time steps were used where necessary for short times ( $\leq 10$  ms). In general, an accuracy of  $\leq 0-15\%$  is expected. For wall loadings in excess of  $1 \times 10^4$  W/cm<sup>2</sup>, smaller  $\Delta x$  and  $\Delta t$  values were used when necessary.

\* On leave of absence from Brookhaven National Laboratory at the Institute for Fusion Studies, Austin, Texas.

$$K \frac{\partial^2 T}{\partial x^2} - \frac{\partial T}{\partial t} = \frac{S_0}{\rho C_p} e^{-\gamma x} \phi(t) \quad (1)$$

If

$$K = \frac{k}{\rho C_p} ,$$

$$\tau = Kt/x^2 \quad (\tau > 0) ,$$

$$X = x/x \quad (0 < X < 1) ,$$

$$D = x^2/K(T_1 - T_0) ,$$

$$\dot{q} = S_0 \phi(t) \exp(-\gamma x) .$$

If

$i$  = Spatial Node Position ,

$n$  = Time Step ,

$$\theta = (T - T_0)/(T_1 - T_0) .$$

$$\theta_{i,n+1} = \lambda \theta_{i-1,n} + (1-2\lambda) \theta_{i,n}$$

$$+ \Delta t D \ddot{q}_{i,n} + \lambda \theta_{i+1,n} , \quad (2)$$

$i = 1$  or  $M+1$  ,  $n \neq 0$  , and where  $\lambda = \Delta t / (\Delta X)^2$ .

$$\lambda \leq \frac{1}{6} \Rightarrow \text{A Stable and Converged Solution} . \quad (3)$$

At  $x = 0$  ,

$$-k \frac{\partial T}{\partial x} = Q_0 \phi(t) - \sigma \epsilon (T^4 - T_{w1}^4) \quad (4)$$

At  $x = L$  ,

$$-k \frac{\partial T}{\partial x} = \sigma \epsilon (T^4 - T_{w2}^4) \quad (5)$$

Then

$$T_{j,k} \times \left[ \frac{T_{j,k} - T_0}{T_{cool} - T_0} \right] \equiv \theta_{j,k} \quad (6)$$

and

$$[T_{cool} = T_1] .$$

Then for Eq. (4)

$$\theta_{i,n} = \theta_{i+1,n} + \frac{\Delta x Q_0 \phi(x^2 \tau / K)}{k [T_{cool} - T_0]} \quad (7)$$

or

$$\theta_{i,n} = \theta_{i+1,n} + \left[ \frac{\Delta x}{k} \right] \frac{[Q_0 \phi(x^2 \tau / K) - \sigma \epsilon (T_{i,n-1}^4 - T_{w1}^4)]}{(T_{cool} - T_0)} \quad (8)$$

and for Eq. (5)

$$\theta_{i+1,n} = \theta_{i,n} - \frac{\sigma \epsilon \Delta x (T_{i+1,n-1}^4 - T_{w2}^4)}{k (T_{cool} - T_0)} \quad (9)$$

Thermal stress model plate restrained in bending only:

$$\sigma_{yy} = \sigma_{zz} = \frac{\alpha E}{1-\nu} \left[ -T + \frac{1}{2L} \int_0^L T(x,t) dx \right] \quad (10)$$

where  $E \equiv$  Young's Modulus (PSI) ,  
 $\alpha \equiv$  Coeff. of Thermal Expansion ( $^{\circ}\text{C}^{-1}$ ) ,  
 $\nu \equiv$  Poisson's Ratio .

Calculated using Simpson's rule:

$$\int_0^L T(x) dx = \frac{\Delta x}{3} [T(1) + 4 \sum_{\text{odd}} T(M) + 2 \sum_{\text{even}} T(M) + T(M+1)] \quad (11)$$

## 2. PARAMETRIC STUDY RESULTS SUMMARY

The parameter study was carried out for a wide range of  $Q_0$  values, between  $1 \times 10^2 \text{ W/cm}^2$  and  $1 \times 10^5 \text{ W/cm}^2$ . A summary of short time ( $< 10 \text{ ms}$ ) results is presented in Fig. 1. It can be seen from the figure that a wall loading of

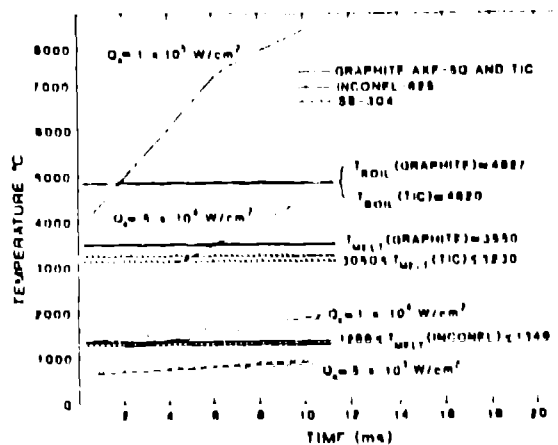


FIGURE 1  
Temperature versus time behavior.

$= 1 \times 10^4 \text{ W/cm}^2$  results in melting of Inconel and SS first wall material and loading of  $= 5 \times 10^4 \text{ W/cm}^2$  result in melting of TIC and Graphite. Thermal material properties are summarized on Tables I through IV.

TABLE I. INCONEL-625

$k$	$= 0.2523 \text{ W cm}^{-1} ^{\circ}\text{C}^{-1}$
$C_p$	$= 0.4102 \text{ J/(gm}^{\circ}\text{C)}$
$\rho$	$= 8.44 \text{ g/cm}^3$
$\alpha$	$= 16.20 \times 10^{-6} \text{ cm/cm/}^{\circ}\text{C}$
$Y_m$	$= 23.1 \times 10^6 \text{ psi (1400}^{\circ}\text{F)}$
$P_{\text{ratio}}$	$= 0.329 \text{ (1400}^{\circ}\text{F)}$
$T_{\text{melt}}$	$= 1288 - 1349^{\circ}\text{C}$

TABLE II. SS-304

$k$	$= 0.2232 \text{ W cm}^{-1} ^{\circ}\text{C}^{-1}$
$C_p$	$= 0.5023 \text{ J/(gm}^{\circ}\text{C)}$
$\rho$	$= 8.005 \text{ g/cm}^3$
$\alpha$	$= 18.54 \times 10^{-6} \text{ cm/cm/}^{\circ}\text{C (1000}^{\circ}\text{C)}$
$Y_m$	$= 22.8 \times 10^6 \text{ psi (1000}^{\circ}\text{C)}$
$P_{\text{ratio}}$	$= 0.32$
$T_{\text{melt}}$	$= 1500^{\circ}\text{C}$

TABLE III. GRAPHITE AXF-5Q

$k$	$= 1.2098 \text{ W cm}^{-1} ^{\circ}\text{C}^{-1}$
$C_p$	$= 0.8372 \text{ J/(gm}^{\circ}\text{C)}$
$\rho$	$= 1.8 \text{ g/cm}^3$
$\alpha$	$= 7.7 \times 10^{-6} \text{ cm/cm/}^{\circ}\text{C}$
$Y_m$	$= 1.6 \times 10^6 \text{ psi}$
$P_{\text{ratio}}$	$= 0.15$
$T_{\text{melt}}$	$= 3550^{\circ}\text{C}$
$T_{\text{subl}}$	$= 3367^{\circ}\text{C}$
$T_{\text{vap}}$	$= 4827^{\circ}\text{C (Boiling Point)}$
$\Delta x$	$= 2.3876 \text{ cm}$
$\Delta x(\text{thermocouple})$	$= 0.3175 \text{ cm}$

TABLE IV. TiC PROPERTIES

$k$	=	$0.440 \text{ W cm}^{-1} \text{ }^{\circ}\text{C}^{-1}$	(1273°K)
$C_p$	=	$0.8833 \text{ J/(gm}^{\circ}\text{C)}$	
$\rho$	=	$4.93 \text{ gm/cm}^3$	
$\alpha$	=	$8.6 \times 10^{-6} \text{ cm/cm/}^{\circ}\text{K}$	
$Y_m$	=	$61 \times 10^6 \text{ psi}$	(1273°K)
$P_{\text{ratio}}$	=	0.20	
$T_{\text{melt}}$	=	$3140 \pm 90^{\circ}\text{C}$	
$T_{\text{boil}}$	=	$4820^{\circ}\text{C}$	
$\Delta x$	=	$20 \times 10^{-6} \text{ m}$	(thickness)

Thermal stress analysis for Inconel, SS-304, Graphite, and TiC was performed as a function of  $Q_0$  for 10 ms and 1 ms energy deposition times. Table V lists the relevant stress failure parameters for the materials of interest, where available. For Inconel-625, stresses in excess of the tensile strength occur for  $Q_0$  greater than  $\geq 1 \times 10^3 \text{ W/cm}^2$ . The same is true for SS-304. For Graphite AXF-5Q, the tensile strength is exceeded for approximately a  $Q_0$  of  $> 1 \times 10^4 \text{ W/cm}^2$ .

### 3. PHYSICAL OBSERVATIONS AND CONCLUSION

A TiC coated AXF-5Q Graphite mushroom limiter, installed in a high field error region (e.g., an experimental vacuum vessel/liner port), was examined during and after a number of ZT-40M discharges, by both

real time filming (camera) and direct physical inspection. The damage, Fig. 2, can best be characterized as evaporation and cracking (see enlargement, Fig. 3) of the TiC coating. The relevant ZT-40M discharge and machine parameters are listed in Table VI.

From the observations of damage and the parametric results calculated it can be inferred that an energy flux of  $1 \times 10^4 \text{ W/cm}^2 < Q_0 < 5 \times 10^4 \text{ W/cm}^2$  was observed over a time scale of  $5 \text{ ms} < \tau_{\text{a0}} < 10 \text{ ms}$  in the field error region, if the model considered is relevant to the phenomenon in question.

### REFERENCE

1. J. A. Fillo, D. Majumdar, and H. Makowitz, "Thermal And Stress Studies (TASS)," DNL-26057 (March 1979).

TABLE VI. ZT-40M PARAMETERS  
GRAPHITE MUSHROOM LIMITER TESTS

Minor plasma radius	0.2 m
Major plasma radius	1.14 m
Toroidal current	120-180 kA
Current Pulse Duration	5-7 ms
Fill Pressure	2.0 mTorr
$T_e$ (on axis)	$\sim 300 \text{ eV}$
$\bar{n}_e$	$\sim 1.5 \times 10^{19} \text{ m}^{-3}$

TABLE V. STRESS MATERIAL PARAMETERS

	<u>SS-304</u>	<u>Inconel-625</u>	<u>TiC</u>	<u>Graphite AXF-5Q</u>
Yield Strength	22,000 psi	42-110 ksi	-----	-----
Ultimate Tensile Strength	56,000 psi	-----	280 MN/m <sup>2</sup>	-----
Compressive Strength	-----	-----	875 MN/m <sup>2</sup>	17,000 psi
Flexural Strength	-----	-----	-----	12,000 psi
Tensile Strength	-----	120-160 ksi	-----	8,000 psi
Tensile Strain to Failure	-----	-----	-----	0.82

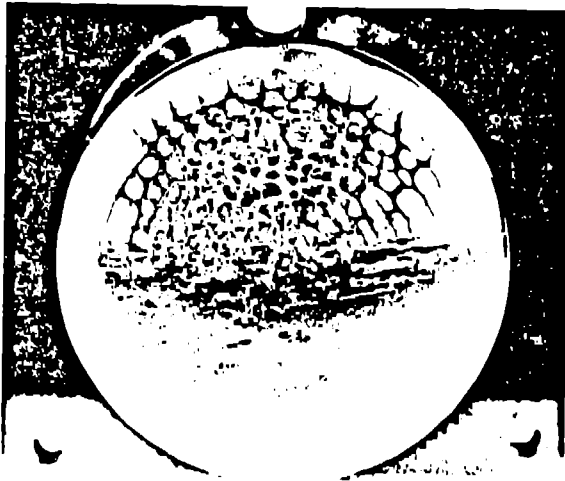


FIGURE 2  
Gross surface damage of TIC coated  
graphite mushroom limiter.

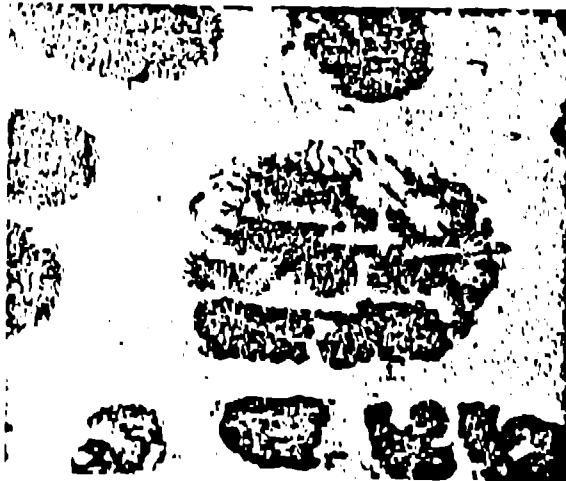


FIGURE 3  
Close-up of limiter damage. TIC surface  
cracking is shown.